JOURNAL OF APPLIED PHYSICS **97**, 1 (2005)

Spatially resolved ferromagnetic resonance: Imaging of ferromagnetic eigenmodes

Aleksandar Puzic, Bartel Van Waeyenberge, Kang Wei Chou, Peter Fischer, Hermann Stoll, and Gisela Schütz
Max-Planck-Institut für Metallforschung, 70569 Stuttgart, Germany

Tolek Tyliszczak
Chemical Science Division, LBNL, Berkeley, California, 94720

Karsten Rott, Hubert Brückl, and Günter Reiss
Fakultät für Physik, Universität Bielefeld, 33501 Bielefeld, Germany

Ingo Neudecker, Thomas Haug, Matthias Buess, and Christian H. Back
Experimentelle Physik, Universität Regensburg, 93053 Regensburg, Germany

(Presented on 9 November 2004)

Fast magnetization dynamics of ferromagnetic elements on sub-micron length scales is currently attracting substantial scientific interest. Studying the ferromagnetic eigenmodes in such systems provides valuable information in order to trace back the dynamical response to the underlying micromagnetic properties. The inherent time structure of third generation synchrotron sources allows for time-resolved imaging (time resolution: 70–100 ps) of magnetization dynamics at soft x-ray microscopes (lateral resolution down to 20 nm). Stroboscopic pump-and-probe experiments were performed on micron-sized Permalloy samples at a full-field magnetic transmission x-ray microscope (XM-1, beamline 6.1.2) at the ALS at Berkeley, CA. Complementary to these time-domain experiments a frequency-domain "spatially resolved ferromagnetic resonance" (SR-FMR) technique was applied to magnetic x-ray microscopy. In contrast to time-domain measurements which reflect a broadband excitation of the magnetization, the frequency-domain SR-FMR technique allows for detailed studies of specific ferromagnetic eigenmodes. First SR-FMR experiments at a scanning x-ray transmission microscope (STXM, ALS, BL 11.0.2) are reported. The sample, a 1×1 μm^2 Permalloy pattern, was excited by an alternating magnetic field with a frequency of 250 MHz. By varying the phase relation between the sine excitation and the x-ray flashes of the synchrotron, the dynamics of a vortex motion eigenmode was investigated in time and space. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1860971]

I. INTRODUCTION

Modern magnetic materials like magnetically ordered thin films, multilayers, micro- and nanostructured systems are of increasing scientific and technological importance. The deeper understanding of fundamental physical properties[1] and the improvement of functionality of magnetic devices like MRAM cells, spin valve systems and fast switching magnetic data storage technologies is closely related to the insight into the magnetization dynamics of their individual layers. Spatially resolved ferromagnetic resonance (SR-FMR), an element-specific imaging technique that will be presented, provides valuable information about the dynamical behavior of laterally patterned magnetic elements. So far, this method was occasionally used in magneto-optical Kerr microscopy.[2] It allows a selective excitation of ferromagnetic resonance modes at GHz and sub-GHz frequencies. The commonly used stroboscopic "pump-and-probe" imaging technique, which reflects a broadband excitation of the magnetization, will be given as a comparison.

The contrast mechanism for both techniques is the "x-ray magnetic circular dichroism (XMCD)" effect, i.e., the dependence of the absorption coefficient of circularly polarized x-rays on the magnetization of a ferromagnetic sample. In combination with x-ray microscopes,[3] the XMCD contrast offers the opportunity for element-specific imaging of magnetic structures. Lateral resolution down to 20 nm can be achieved with state of the art x-ray optics (Fresnel zone plates). By taking advantage of the inherent time structure of the third generation synchrotron sources, stroboscopic time-resolved measurements were reported,[4,5] with a time resolution of 70–100 ps given by the width of the x-ray flashes and the time jitter of the synchronization electronics.

II. TIME-DOMAIN MEASUREMENTS: PUMP-AND-PROBE EXPERIMENTS

Stroboscopic pump-and-probe experiments in time-domain were performed at the full-field magnetic transmission x-ray microscope XM-1 (beamline 6.1.2) at the advanced light source (ALS) at Berkeley, CA. The samples investigated were 1×1 μm^2 and 2×2 μm^2 Permalloy ($Ni_{80}Fe_{20}$) patterns, 50 nm thick [cf. Fig. 1(a)], prepared lithographically on a 150 nm thick and 10 μm wide Cu–Al stripline deposited onto a 100 nm thick Si_3N_4 membrane. Both patterns exhibit a magnetic Landau structure as sketched in Fig. 1(a). The XMCD effect is only sensitive to the projection of the magnetization on the propagation direc-

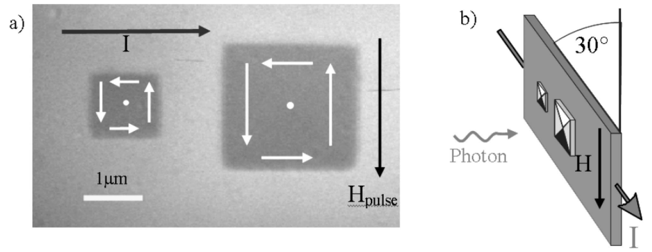

FIG. 1. **(a)** Permalloy patterns, 1×1 μm^2 and 2×2 μm^2, 50 nm thick on a Cu–Al stripline (150 nm thick). The orientations of the Landau structures of the magnetic samples are indicated by arrows. For pump-and-probe experiments an in-plane magnetic field pulse H_{pulse} (pump) is generated by a pulsed electrical current I. **(b)** Schematic of the stripline tilted by 30° with respect to a plane perpendicular to the photon beam. In this configuration the time-dependence of the in-plane magnetization of the samples can be detected by the x-ray flashes (probe) using the XMCD effect.

tion of the x-rays. Hence, in order to image the in-plane magnetization, the sample was tilted by 30° with respect to the plane perpendicular to the incoming photon beam [cf. Fig. 1(b)].

The excitation of the magnetization in a magnetic sample is provided by an electric current pulse "I" [cf. Fig. 1(a)] inducing an in-plane magnetic pump–pulse "H_{pulse}" parallel to the surface of the sample. The temporal evolution of magnetization is probed by x-ray flashes of the synchrotron, which arrive at variable time delays at the sample site with respect to the magnetic pulses. In that way stroboscopic XMCD images were recorded at the full-field XM-1 microscope in two-bunch mode. The accumulation time for each image was 4 s and up to 500 images were summed up for each time delay step. Afterwards, the polarity of the electronic pulse was reversed and a second image stack was accumulated. These two image stacks, recorded for positive and negative electronic pulse polarity, respectively, were subtracted from each other for each time delay step, resulting in differential images. A detailed interpretation of the differential images is given in Sec. III. The temporal evolution of the magnetization dynamics in both Permalloy elements for different time delays between the magnetic field pump-pulses and the probing x-ray flashes is shown in Fig. 2. The pump-and-probe measurements at a negative delay time of −100 ps (first picture in Fig. 2) shows no dynamic effect, as the x-ray flashes arrive before the magnetic pump-pulses. At positive delay times the contrast of the "cross" of the smaller 1×1 μm^2 sample is inverted at 2500 ps compared to the 400 ps delay time (indicating half a turn of the gyrating vortex movement) and restored again at 4000 ps delay time (full turn). Unlike in the smaller sample, the contrast inversion of the cross of the large 2×2 μm^2 pattern is observed much later at a delay time of 4000 ps. This indicates that the vortex movement in the 2×2 μm^2 sample has about half the speed of the smaller 1×1 μm^2 sample. The image sequence shown in Fig. 2 also demonstrates that almost all "nonmagnetic" and "nondynamic" contrast contributions are effectively eliminated by the differential imaging technique.

III. FREQUENCY-DOMAIN MEASUREMENTS: SPATIALLY RESOLVED FMR

Complementary to time-domain "pump-and-probe" experiments, a frequency-domain "Spatially resolved ferromagnetic resonance (SR-FMR)" technique was applied to magnetic x-ray microscopy. The SR-FMR method allows detailed studies of specific ferromagnetic eigenmodes, in contrast to the pump-and-probe technique, which reflects a broadband excitation of the magnetization.

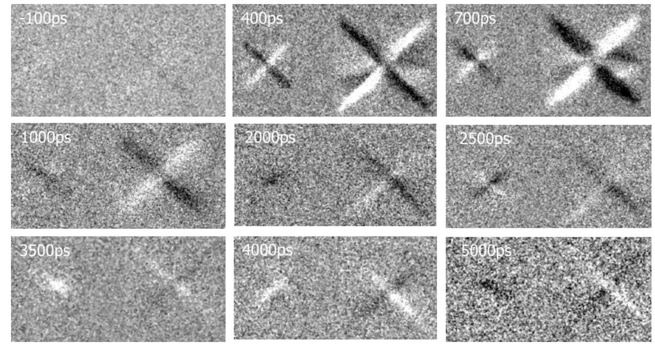

FIG. 2. Differential images of the magnetization dynamics at different time delays between the magnetic pump-pulses and the probing x-ray flashes. The "dots" and "crosses" are the result of a differential noise reduction technique suppressing all "nondynamic" effects (cf. Sec. III). At a delay time of −100 ps (first picture) the x-ray flashes arrive before the magnetic pump-pulses, thus no dynamic effects are observed. For the smaller 1×1 μm^2 sample the contrast of the cross is inverted at 2500 ps delay (indicating a half turn of the gyrating vortex movement) and restored at 4000 ps delay (full turn). An inversion of the contrast of the cross (half a turn) is observed in case of the larger 2×2 μm^2 pattern at a later delay time showing a vortex movement of about half the speed of the smaller sample.

In SR-FMR experiments the magnetization of the sample is excited by a continuous RF sine wave. In that way spin precession modes (in the GHz frequency range) and modes of magnetic vortex movement (in the sub-GHz frequency range) can be studied. The frequency of the excitation has to be phase synchronized with the x-ray flashes of the synchrotron. Thus only multiples of the synchrotron bunch frequency can be addressed. In the "few-bunch" operation modes commonly used for time-resolved imaging (like in the "two-bunch" mode at the ALS where the frequency grid is about 3 MHz) this is not a real limitation as most ferromagnetic resonances are broad.

The SR-FMR setup was built up at the STXM[6] (ALS, beamline 11.0.2). The results for the 1×1 μm^2 element shown in Fig. 1(a) were recorded at 250 MHz excitation frequency. This frequency is near to the vortex oscillation frequency observed in this sample (cf. Fig. 2) and equals to half of the synchrotron's RF frequency. During the measurements, the phase was changed by 180° at a 10 kHz rate and the amount of transmitted photons were recorded in two separate counter channels. In this way a direct differential image could be derived by subtracting the two channels. By delaying the excitation signal, the response of the sample was imaged in 45° steps as shown in Fig. 3. The sequence of differential images can be interpreted as a rotation of the magnetic vortex around the center of the sample (cf. Sec. III).

IV. DIFFERENTIAL IMAGES AND THEIR INTERPRETATION

The "differential images" in Figs. 2 and 3, which appear as "dots" and "crosses" demonstrate a very high sensitivity

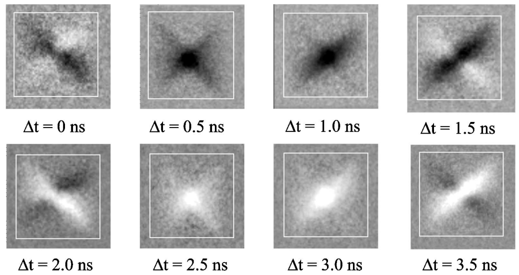

FIG. 3. Spatially resolved FMR images taken at different delays (corresponding to 45° phase angle steps) of the 250 MHz continuous RF excitation with respect to the probing X-ray flashes. The "dots" and "crosses" (cf. Sec. III) are the results of a differential imaging technique used in order to suppress all "nonmagnetic" and "nondynamic" effects (see Sec. III). These structures can be explained by gyration of the magnetic vortex.

of the differential imaging technique to magnetization dynamics. An explanation how to derive the movement of the magnetic vortex from the dots and crosses observed in Figs. 2 and 3 is given in Fig. 4. Examples of experimentally acquired differential images are shown in the most left column. The drawings in columns I and II differ by a 180° phase shift of the vortex movements due to an inverted electronic pump–pulse polarity (for pump-and-probe measurements) or a 180° phase shift in the sine excitation (SR-FMR measurements). The differences of both drawings, given at the most right column show the same black and white dots and crosses as observed in the experimental results. Recalling the orientation of the Landau domains in respect to the photon direction, the left and right domains will not contribute to the magnetic contrast as the magnetization is perpendicular to the photon propagation direction. The top and bottom domains, which have a component of their magnetization along

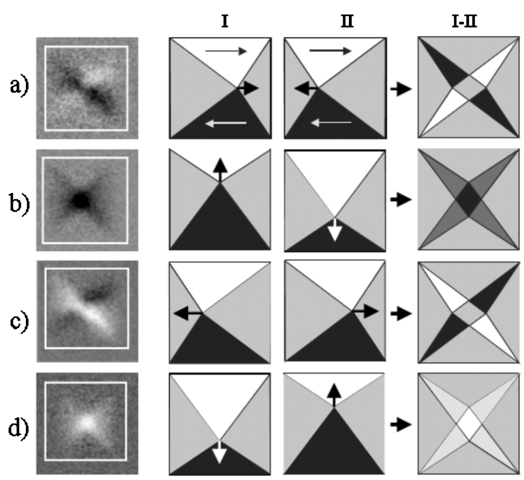

FIG. 4. Explanation of the origin of the "dots" and crosses" observed in Figs. 2 and 3. The pictures in columns I and II differ by a 180° phase change of the vortex gyration due to an inverted electronic pump-pulse polarity (for pump-and-probe measurements) or a 180° phase change in the sine excitation (spatially resolved FMR measurements). The differences of both pictures (most right column) result in the same black and white dots and crosses as observed in the experimental result (pictures in the most left column, cf. also Figs. 2 and 3). Examples are given for following vortex movements (a) to the right, (b) up, (c) to the left, (d) down.

or against the photon propagation direction, will have opposite contrast contributions. Considering a movement of the magnetic vortex as a consequence of the excitation by an in-plane magnetic field, a contrast in the differential image will only appear near the domain walls where movements result in contributions of different domains. It can easily be understood that a movement up (or down) creates a full dark (or white) cross and a movement left (or right) creates a white–black cross (or black–white).

V. CONCLUSIONS AND OUTLOOK

Spatially resolved ferromagnetic resonance (SR-FMR), as a novel element-specific imaging technique, was implemented to a scanning transmission x-ray microscope (STXM). Complementary to the pump-and-probe technique in time-domain, the SR-FMR is a powerful tool for frequency-domain studies of specific ferromagnetic eigenmodes in laterally patterned magnetic samples. The dynamic response of a ferromagnetic mode of interest can be significantly improved by SR-FMR, as more excitation power is concentrated to that specific mode. This may allow future studies of non-linear dynamic effects and has a potential to improve element-specific measurements of magnetization dynamics in very thin magnetic multilayers.

ACKNOWLEDGMENTS

The authors would like to thank all of the people at the Advanced Light Source, the Center for x-ray Optics, the Bielefeld University and the Regensburg University who were involved in these measurements and in the preparation of the samples. In particular we would like to thank Greg Denbeaux for his continuous support at the XM-1 x-ray microscope, Andreas Scholl, Heinz Dieter Carstanjen, Yves Acremann, and Thomas Eimüller for many fruitful discussions, Bill Bates and Walter Plenert for building up precision mechanics parts and Mike Fahmie, Richard Weber and Siegfried Kollert for their expertise in fast logic and GHz RF components. Financial support by the DFG (priority program 'Ultrafast Magnetization Processes') and the Flemish government (Attraction Pole IAP 5/01) is gratefully acknowledged.

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